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Dynamics of Exploding Plasma within a Magnetized Plasma

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Dynamics of exploding plasma within a magnetized plasma

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This memo describes several possible laboratory experiments on the dynamics of an exploding plasma in a background magnetized plasma. These are interesting scientifically and the results are applicable to energetic explosions in the earth's ionosphere (DOE Campaign 7 at LLNL). These proposed experiments are difficult and can only be performed in the new LAPD device at UCLA. The purpose of these experiments would be to test numerical simulations, theory and reduced models for systems performance codes. The experiments are designed to investigate the affect of the backgorund plasma on

(1) the maximum diamagnetic bubble radius given by Eq. 9 below

(2) the Alfven wave radiation efficiency produced by the induced current J_A (Eqs. 10-12)

These experiments involve measuring the bubble radius using a fast gated optical imager as in Ref [1] and the Alfven wave profile and intensity as in Ref [2] for different values of the exploding plasma energy, background plasma density and temperature, and background magnetic field. These experiments extend the previously successful experiments [2] on Alfven wave coupling. We anticipate that the proposed experiments would require 1-2 weeks of time on the LAPD. We would perform PIC simulations in support of these experiments in order to validate the codes. Once validated, the PIC simulations would then be able to be extended to realistic ionospheric conditions with various size explosions and altitudes. In addition to the Alfven wave coupling, we are interested in the magnetic containment and transport of the exploding "debris" plasma to see if the shorting of the radial electric field in the magnetic bubble would allow the ions to propagate further. This has important implications in an ionospheric explosion because it defines the satellite damage region. In these experiments, we would field fast gated optical cameras to obtain images of the plasma expansion, which could then be correlated with magnetic probe measurements. In this regard, it would be most helpful to have a more powerful laser more than 10J in order to increase the extent of the magnetic bubble.

Background

Consider an exploding plasma with total energy E_d and total number of ions N_d expanding into a vacuum magnetic field B. If the ions are unmagnetized, they are stopped a radius R_{bo} given by

$$e\, E\, R_{bo} \sim E_d / N_d \qquad (1)$$

where E is an electric field that develops between the ions and magnetized electrons. This field produces an electron drift current

$$J_\theta \sim (N_d/4\pi R_{bo}^2 d)\, ecE/B \qquad (2)$$

Where d is the radial thickness of the exploding plasma. This current produces a diamagnetic field perturbation

$$\delta B \sim 4\pi\, J_\theta\, d/c \sim /R_{bo}^3 B \qquad (3)$$

Equations 1-3 can then be rewritten as

$$E_d = \frac{B^2}{8\pi}\frac{4\pi R_{bo}^3}{3} \tag{4}$$

which is interpreted as energy balance, namely, that the final radius of the diamagnetic cavity produced the exploding plasma is obtained when its total kinetic energy equals the total displaced magnetic energy. This has been checked [1] for a plasma exploding into a vaccum.

However, there are two complications when there is a magnetized background plasma of number density n_o. First, the background plasma is swept up by the exploding plasma and must be energized by it such that energy balance is modified to

$$E_d = \frac{B^2}{8\pi}\frac{4\pi R_b^3}{3} + \frac{\rho_o V_d^2}{2}\frac{4\pi R_b^3}{3} \tag{5}$$

where ρ_o is the mass density of the background plasma and V_d is the expansion velocity of the exploding plasma. This effectively reduces the maximum radius of the diamagnetic cavity to

$$\frac{R_b}{R_{bo}} \sim \left[1+\left(\frac{V_v}{V_A}\right)^2\right]^{-1/3} \tag{6}$$

The second effect has both local and global implications in that the electric field in Eq. 1 can be shorted out by electron currents in the background plasma. This will reduce the depth of the diamagnetic cavity δB and also the retarding force on the expanding ions so that they will be transported to larger radius. In addition, the induced current J_A in the background plasma will generate Alfven waves. Using Ampere's lae, the Alfven wave magnetic field is

$$B_A \sim J_A R_b 2\pi/c \tag{7}$$

with a period of $3R_b/V_d$. Then, the energy radiated into Alfven waves can be estimated as

$$E_A = \frac{B_A^2}{8\pi} 2\pi R_b^2 V_A \frac{3R_b}{V_d} \sim \frac{3\pi^2}{c^2} J_A^2 \frac{V_A}{V_d} R_b^5 \tag{8}$$

The should be included in energy balance

$$E_d = \frac{B^2}{8\pi}\frac{4\pi R_b^3}{3} + \frac{\rho_o V_d^2}{2}\frac{4\pi R_b^3}{3} + E_A \tag{9}$$

These affects are important for modelling an energetic explosion in the ionosphere because the energetic plasma can destroy satelites and the Alfven waves can propogate over the entir earth and induce power disruption. Such effects are difficult to calculate and must be checked with experiments, such as those proposed here.

Proposed study

They key uncertainty in this model is the magnitude and distribution of the Alfven wave current induced in the background plasma. Initial experiments [2] performed to measure this current in the LAPD obtained very interesting results. PIC simulations of these experiments obtain $J_A \sim 10^{10}$ statamps/cm^2 for LAPD conditions, $n_o \sim 2\ 10^{12}$ cm^{-3} and $V_d \sim 10^7$ cm/s. Such a value can be obtained by using the plasma expansion speed

$$J_A \sim n_o e V_d \sim 10^{10} \text{ statamp/cm}^2 \quad (10),$$

or the Alfven speed

$$J_A \sim 0.1\, n_o e V_A \sim 10^{10} \text{ statamp/cm}^2 \quad (11),$$

or the electron thermal speed at $T_e \sim 2$ eV

$$J_A \sim 0.1\, n_o e V_e \sim 10^{10} \text{ statamp/cm}^2 \quad (12).$$

It is important to differentiate among these "explanation" because they will predict very different values for a hypothetical megaton explosion at 400 km height in the ionosphere[3, 4]. For these conditions, $n_o \sim 2\ 10^5$ cm^{-3}, $B \sim 0.3$ g, $T_e < 0.1$ eV, $V_d \sim 1.5\ 10^8$ cm/s, $E_d \sim 10^{22}$ ergs, we estimate very different values of

$$J_A \sim n_o e V_d \sim 15{,}000 \text{ statamp/cm}^2 \quad (13),$$

or

$$J_A \sim 0.1\, n_o e V_A \sim 500 \text{ statamp/cm}^2 \quad (14),$$

or

$$J_A \sim 0.1\, n_o e V_e < 200 \text{ statamp/cm}^2 \quad (15).$$

These differences are very important since the Alfven wave radiation efficiency scales as J_A^2.

In addition to measuring the wave coupling, it is important to obtain gated images of the exploding plasma in order to ascertain how far it is transported. This can be done with our Gated Optical Imager (GOI) and the associated CCD cameras. These images can then be compared to magnetic probe measurements in the local magnetic bubble. They can also be compared with images taken at LLNL in a vacuum magnetic field in which strong Rayleigh-Taylor type instabilities caused spikes of plasma to be transported well beyond the magnetic containment radius.

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References

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